

Front propagation in $A+B \rightarrow 2A$ reaction under subdiffusion

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Abstract

We consider an irreversible autocatalytic conversion reaction $A + B \rightarrow 2A$ under subdiffusion described by continuous time random walks. The reactants' transformations take place independently on their motion and are described by constant rates. The analog of this reaction in the case of normal diffusion is described by the Fisher-Kolmogorov-Petrovskii-Piskunov (FKPP) equation leading to the existence of a nonzero minimal front propagation velocity which is really attained by the front in its stable motion. We show that for subdiffusion this minimal propagation velocity is zero, which suggests propagation failure.

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I. INTRODUCTION

The theory of reactions under subdiffusion had attracted recently considerable attention both because of theoretical and mathematical challenges posed by such problems, and also due to their growing practical relevance for description of phenomena taking place in porous media (as exemplified by geophysical structures) and in crowded interior of living cells (e.g. Refs. [1–3]). Several recent works were dedicated to the theoretical description of Turing patterns and of fronts in such systems [4–7]. Thus Ref.[7] concentrates on the front behavior in the system which in the case of the normal diffusion would be described by the Fisher-Kolmogorov-Petrovskii-Piskounov (FKPP) equation and shows, that under the description adopted, there exists a (minimal) stable propagation velocity of such front, just like it is the fact under normal diffusion. As we proceed to show, this is not always the case. Considering the fully irreversible analog of the reaction discussed in Ref.[7] under conserved overall concentration we show that the minimal propagation velocity is zero, which corresponds essentially to propagation failure. The system we consider here corresponds to the $A + B \rightarrow 2A$ irreversible reaction, which in the case of the normal diffusion is also described by the FKPP equation.

The FKPP equation [8], proposed by R. A. Fisher in 1937 [9] as a model for propagation of a favorable gene in a population, corresponds to a mathematical description of the (irreversible or reversible) reaction whose main stage is a bimolecular autocatalytic conversion $A + B \rightarrow 2A$. Initially the whole system consists of particles (individuals) of type B. The introduction of the A-individuals into some bounded spacial domain (which is described by an initial condition sharply concentrated in vicinity of the origin of coordinates) leads to a propagation of a front of A into the B-domain. Physically this corresponds to a front propagating into the unstable state. Under normal diffusion, the process is described by a partial differential equation

$$\frac{\partial A}{\partial t} = D \frac{\partial^2 A}{\partial x^2} + kAB$$

for an irreversible reaction, where the initial concentration of B is assumed to be homogeneous and equal to $B(x, 0) = B_0$ everywhere except for the vicinity of the origin. In this case the overall concentration is conserved, due to the local stoichiometry of the reaction which does not change the number of particles. Here and in what follows we denote the nature of particles in reaction equations by Roman letters, while the corresponding concentrations or

particle numbers are written in *italic*.

Using the conservation law, the corresponding reaction-diffusion equation can be rewritten as

$$\frac{\partial A}{\partial t} = D \frac{\partial^2 A}{\partial x^2} + kAB_0 - kA^2. \quad (1)$$

The equation for the reversible reaction has the same form but different coefficients in front of the two last terms in the right hand side (e.g. [10]). The FKPP equation is the simplest model of front propagation into an unstable state and serves as a paradigmatic model for many related phenomena.

The front velocity in the genuine FKPP equation is determined by that of its leading edge, i.e. by the behavior of concentrations for $x \rightarrow \infty$. Since the concentration of converted particles in this leading edge is very small, the equation can be linearized, and the possible velocity of the front is given by the analysis of the *linear* propagation problem [11, 12]. For the FKPP equation, Eq.(1) leads for $x \rightarrow \infty$ (and $B \rightarrow B_0$) to

$$\frac{\partial A}{\partial t} = D \frac{\partial^2 A}{\partial x^2} + kB_0A \quad (2)$$

(or by the corresponding equation for $\delta B = B_0 - B = A$) having the exponential propagating solution $A \simeq \exp(-x + vt)$ for all $v \geq 2\sqrt{DkB_0}$ where the condition on v is imposed by the natural boundary condition $A = 0$ for $x \rightarrow \infty$ and by forbidding oscillatory behavior. Further analysis shows that the minimal velocity $v = 2\sqrt{DkB_0}$ is exactly the one attained, which fact is known as the marginal stability principle. The front in the FKPP system is an example of the so-called “pulled front”, as it is “pulled” into the unstable state by its leading edge, and its propagation velocity does not depend on what happens in the interior of the front where the conversion of the most particles takes place.

Modeling reaction phenomena in subdiffusive media requires some preliminary assumptions on the nature of the transport process. Parallel to Refs.[13, 14] we assume that the subdiffusive motion on a mesoscopic scale is a consequence of trapping of particles on a mesoscopic scale, due to e.g. the bottlenecks connecting the voids in a porous system, while on a microscopic scale within the pores the $A + B \rightarrow 2A$ reaction takes place in a homogeneous solution and follows the mass action law. The local conservation of particle concentration is an inherent property of such systems which also holds on the mesoscopic scale. The model adopted corresponds therefore to the systems which at smaller scales consists of compartments in which the reaction follows the usual kinetic laws, while the subdiffusive transport

between the compartments is described by continuous time random walks with a distribution of sojourn times which may lack the first moment. As we proceed to show, due to the coupling between the reaction and transport term inherent for subdiffusion [13, 14], the behavior of the reaction front under subdiffusion and under the conditions discussed above is vastly different from the one under normal diffusion. The minimal propagation velocity of the front is zero, which corresponds to propagation failure. The preliminary results of our numerical simulations confirm that the front's velocity decays with time. These numerical results will be discussed in detail elsewhere.

II. THE $A + B \rightarrow 2A$ REACTION UNDER SUBDIFFUSION

A. General considerations

Following the same procedure as in [4, 13] one obtains the equations for the particle concentrations as a consequence of the conservation laws. Discretizing the system into compartments (sites) numbered by the index i we get for the mean numbers of B-particles at site i

$$\dot{B}_i(t) = \frac{1}{2}j_{i-1}^-(t) + \frac{1}{2}j_{i+1}^-(t) - j_i^-(t) - kA_i(t)B_i(t). \quad (3)$$

Eq. 3 is a local balance equation for the number of B-particles at site i with $j_i^-(t)$ being loss fluxes of particles B from the site i at time t given by

$$j_i^-(t) = \psi(t)P_B(t, 0)B_i(0) + \int_0^t \psi(t-t')P_B(t, t') \left[\dot{B}_i(t') + j_i^-(t') + kA_i(t')B_i(t') \right] dt' \quad (4)$$

$$P_B(t, t') = \exp \left[-k \int_{t'}^t A_i(t'') dt'' \right]. \quad (5)$$

The first term on the right hand side of Eq.(4) for the corresponding flux gives the contribution of those B-particles that were at i from the very beginning and survived until t . The second term describes the particles, that arrived at i at a time t' and did neither react nor perform a jump until t . Equation (5) gives the survival probability of B-particles. The

A-concentration is then given by

$$\dot{A}_i(t) = \frac{1}{2}f_{i-1}^-(t) + \frac{1}{2}f_{i+1}^-(t) - f_i^-(t) + kA_i(t)B_i(t) \quad (6)$$

$$\begin{aligned} f_i^-(t) &= \psi(t)P_A(t,0)B_i(0) + \psi(t)A_i(0) \\ &\quad + \int_0^t \psi(t-t') \left[\dot{A}_i(t') + f_i^-(t') - kA_i(t')B_i(t') \right] dt' \\ &\quad + \int_0^t \psi(t-t')P_A(t,t') \left[\dot{B}_i(t') + j_i^-(t') + kA_i(t')B_i(t') \right] dt' \end{aligned} \quad (7)$$

$$P_A(t,t') = 1 - P_B(t,t') \quad (8)$$

The loss fluxes for A-particles are denoted through $f_i(t)$. The first term on the right hand side of Eq.(7) corresponds to the particles that were at i from the beginning and converted from B to A until t . The second term represents the A-particles that were at i from the very beginning. The third and fourth term describe the particles that arrived at i at a time t' as A-particles, or arrived as B-particles and reacted until t . The probability P_A to gain new A-particles arises from the conservation of the total number of particles and the probability P_B that the B-particles react. The A-concentration depends on the B-concentrations at all previous times.

Equations (3-8) are consistent with the conservation of the total number of particles in the reaction $A + B \rightarrow 2A$. Let $C_i = A_i + B_i$ be the total mean particle number at i and $g_i^-(t) = f_i^-(t) + j_i^-(t)$ the total loss flux of particles at i . From Eqs. (3, 6) we obtain the balance equation:

$$\dot{C}_i(t) = g_i^+(t) - g_i^-(t) = \frac{1}{2}g_{i-1}^-(t) + \frac{1}{2}g_{i+1}^-(t) - g_i^-(t). \quad (9)$$

From Eqs.(4, 7) follows that

$$\begin{aligned} g_i^-(t) &= \psi(t)[B_i(0) + A_i(0)] + \int_0^t \psi(t-t') \\ &\quad \times \left[\dot{B}_i(t') + \dot{A}_i(t') + f_i^-(t') + j_i^-(t') \right] dt' \\ &= \psi(t)C_i(0) + \int_0^t \psi(t-t') \left[\dot{C}_i(t') + g_i^-(t') \right] dt'. \end{aligned} \quad (10)$$

This equation can be solved by means of the Laplace transform,

$$\tilde{g}_i^-(u) = \frac{u\tilde{\psi}(u)}{1 - \tilde{\psi}(u)}\tilde{C}_i(u), \quad (11)$$

which yields a diffusion equation for $C_i(t)$ in the Markovian case $\psi(t) = \frac{1}{\tau} \exp\left[-\frac{t}{\tau}\right]$, and a subdiffusion equation in the non-Markovian case $\psi(t) \propto t^{-1-\alpha}$, i.e. shows that the behavior

of the total particle concentration is diffusive or subdiffusive, respectively. Moreover, if we choose the initial condition in a way that $C_i(t) = \text{const}$, the total number of particles is also locally conserved, $C_i(t) = C_i(0) = C_0$. This reduces the overall problem to the one for only one species. Passing to the continuous variables $x = ai$ we obtain:

$$\begin{aligned}\dot{B}(x, t) &= \frac{a^2}{2} \Delta j^-(x, t) - k(B_0 - B(x, t))B(x, t) \\ j^-(x, t) &= \psi(t)P_B(x, t, 0)B(x, 0) + \int_0^t \psi(t - t')P_B(x, t, t') \times \\ &\quad \times \left[\dot{B}(x, t') + j^-(x, t') + k(B_0 - B(x, t'))B(x, t') \right] dt' \\ P_B(x, t, t') &= \exp \left[-k \int_{t'}^t (B_0 - B(x, t'')) dt'' \right].\end{aligned}\tag{12}$$

where the concentration of B is given by $B(x, t) = B_i(t)/a^3$, and the corresponding dimensional constant is absorbed into a new reaction rate $k = \kappa a^3$. The concentration B_0 is set to unity in what follows. Eq.(12) can be rewritten in a form following from the equations of Ref.[15] for the irreversible case:

$$\begin{aligned}\dot{B}(x, t) &= -k(1 - B(x, t))B(x, t) + \frac{a^2}{2} \Delta \int_0^t M(t - t') \\ &\quad \times B(x, t') \exp \left[- \int_{t'}^t k(1 - B(x, t'')) dt'' \right] dt'\end{aligned}\tag{13}$$

with $\tilde{M}(u) = u\tilde{\psi}(u)/[1 - \tilde{\psi}(u)]$.

B. Leading edge linearization

To analyze the behavior in the leading edge we note that $A(x, t) = 1 - B(x, t)$ becomes small for $x \rightarrow \infty$ and hence

$$\begin{aligned}\frac{\partial B}{\partial t} &= \frac{a^2}{2} \int_0^t \Delta \left\{ M(t - t')B(x, t') \exp \left[-k \int_{t'}^t (1 - B(x, t'')) dt'' \right] \right\} dt' \\ &\quad - k(1 - B(x, t))\end{aligned}\tag{14}$$

where we have interchanged the sequence of differentiation over x and temporal integration. For $x \rightarrow \infty$ we have $\exp \left[-k \int_{t'}^t (1 - B(x, t'')) dt'' \right] \rightarrow 1$ so that the integrand can be put into the form

$$\begin{aligned}M(t - t') &\left[\frac{\partial^2 B(x, t')}{\partial x^2} + 2 \frac{\partial B(x, t')}{\partial x} \int_{t'}^t k \frac{\partial B(x, t'')}{\partial x} dt'' + B(x, t') \int_{t'}^t k \frac{\partial^2 B(x, t'')}{\partial x^2} dt'' \right. \\ &\quad \left. + B(x, t') \left(\int_{t'}^t k \frac{\partial B(x, t'')}{\partial x} dt'' \right)^2 \right].\end{aligned}$$

We now assume $B(x, t)$ to be $1 - A_0 \exp[-\lambda(x - vt)]$ for large x , i.e. consider a wavefront with an exponentially decaying leading edge moving at a constant velocity v . Inserting this into (14) and retaining only the terms of the first order in A_0 , we get

$$\begin{aligned}
-\frac{\partial}{\partial t}(A_0 \exp[-\lambda(x - vt)]) &= -kA_0 \exp[-\lambda(x - vt)] \\
&+ \frac{a^2}{2} \int_0^t M(t - t') \left[-\lambda^2 A_0 \exp[-\lambda(x - vt')] \right. \\
&+ \frac{k\lambda}{v} A_0 \exp[-\lambda(x - vt')] - \frac{k\lambda}{v} A_0 \exp[-\lambda(x - vt)] \left. \right] dt' \\
&= -kA_0 \exp[-\lambda(x - vt)] \\
&+ \frac{a^2}{2} A_0 \left[-\lambda^2 + \frac{k\lambda}{v} \right] \int_0^t M(t - t') \exp[-\lambda(x - vt')] dt' \\
&- \frac{a^2}{2} \frac{k\lambda}{v} A_0 \exp[-\lambda(x - vt)] \int_0^t M(t - t') dt', \tag{15}
\end{aligned}$$

with the memory kernel $\tilde{M}(u) = u\tilde{\psi}(u)/(1 - \tilde{\psi}(u))$. We note that the traditional way to proceed is first to linearize the equation and then to insert the exponential solution, however, since the solution of the linearized equation is anyhow an exponential we can also proceed the other way around, saving on tedious calculations.

a. Markovian case Let us first show that for the Markovian case of exponential waiting time distribution the standard expression for the minimal velocity of the stable propagation is reproduced. Taking $\psi(t) = \frac{1}{\tau} \exp[-\frac{t}{\tau}]$, one obtains $M(t - t') = \frac{1}{\tau} \delta(t - t')$ and

$$\begin{aligned}
0 &= \frac{\partial}{\partial t}(A_0 \exp[-\lambda(x - vt)]) - kA_0 \exp[-\lambda(x - vt)] \\
&+ \frac{a^2}{2\tau} A_0 \exp[-\lambda(x - vt)] \left[-\lambda^2 + \frac{k\lambda}{v} - \frac{k\lambda}{v} \right] \\
&= \lambda v \exp[-\lambda(x - vt)] - kA_0 \exp[-\lambda(x - vt)] - \frac{a^2}{2\tau} \lambda^2 A_0 \exp[-\lambda(x - vt)]
\end{aligned} \tag{16}$$

which for $z = x - vt$, $z \rightarrow \infty$ leads us to the following equation:

$$\frac{a^2}{2\tau} \lambda^2 - v\lambda + k = 0.$$

This is the standard dispersion relation for the FKPP front, showing that real values of λ (corresponding to physically sound solutions with nonnegative concentrations) are only possible for $v \geq v_{min} = 2\sqrt{a^2 k / 2\tau} \equiv 2\sqrt{Dk}$ with $D = a^2 / 2\tau$ being the diffusion coefficient (note that B_0 is set to unity). Note that the corresponding result emerges due to the cancellation of two terms of different nature in Eq.(16), which, as we proceed to show, does not take place in the non-Markovian case.

b. Non-Markovian case We now assume the waiting time pdf to decay as a power law $\psi(t) \propto t^{-1-\alpha}$, $0 < \alpha < 1$ for large t . With $\hat{t} = t - t'$ we get

$$\begin{aligned} \int_0^t M(t-t') \exp[\lambda v t'] dt' &= \exp[\lambda v t] \int_0^t M(\hat{t}) \exp[-\lambda v \hat{t}] d\hat{t} \\ &= \exp[\lambda v t] \tilde{M}(\lambda v). \end{aligned}$$

and moreover that

$$\int_0^t M(t-t') \exp[\lambda v t'] dt' = \frac{const}{\tau^\alpha} t^{\alpha-1},$$

so that the last term in (15) vanishes for large t . Altogether we have then:

$$\begin{aligned} \frac{\partial}{\partial t} (1 - A_0 \exp[-\lambda(x-vt)]) &= -k A_0 \exp[-\lambda(x-vt)] \\ &\quad + \frac{a^2}{2} A_0 \exp[-\lambda(x-vt)] \left[(-\lambda^2 + \frac{k\lambda}{v}) \tilde{M}(\lambda v) \right], \end{aligned}$$

and with $z = x - vt$

$$\begin{aligned} -\lambda v A_0 \exp[-\lambda z] &= -k A_0 \exp[-\lambda z] \\ &\quad + \frac{a^2}{2} A_0 \exp[-\lambda z] \left[(-\lambda^2 + \frac{k\lambda}{v}) \tilde{M}(\lambda v) \right]; \\ 0 &= -\lambda v + k + \frac{a^2}{2} (\lambda^2 - \frac{k\lambda}{v}) \tilde{M}(\lambda v) \end{aligned} \tag{17}$$

For example, taking $\psi(t)$ to be given by a Mittag-Leffler function $\psi(t) = E_\alpha[-(t/\tau)^\alpha]$, we have exactly $\tilde{\psi}(u) = [1 + (u\tau)^\alpha]^{-1}$ and $\tilde{M}(u) = \tau^{-\alpha} u^{1-\alpha}$, so that

$$0 = -\lambda v + k + \frac{a^2}{2\tau^\alpha} (\lambda^2 - \frac{k\lambda}{v}) (\lambda v)^{1-\alpha}.$$

This equation is equivalent to

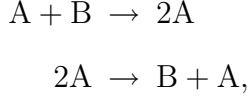
$$(v\lambda - k) \left(\frac{a^2}{2\tau^\alpha} \lambda^{2-\alpha} v^{-\alpha} - 1 \right) = 0 \tag{18}$$

and always possesses two nonnegative roots. Therefore the minimal propagation velocity in this case is zero. The propagation failure corresponds essentially to a continuum approaching of $v_{min} \propto \sqrt{D}$ to zero for the case when $D \rightarrow 0$ as it is the case in subdiffusion.

III. COMPARISON WITH A RELATED MODEL OF REF.[7]

Our result here differs from the one of Yadav et al.[7], where the stable front propagation with the constant velocity was found. The authors of Ref.[7] consider a situation in which

the A-particles undergo a reversible reaction corresponding to the branching-coalescence scheme,



which for the Markovian case is also described by the FKPP equation. The equation used in Ref.[7] for the non-Markovian case reads:

$$\begin{aligned} \frac{\partial A(x, t)}{\partial t} = & kA(x, t) - k_1 [A(x, t)]^2 \\ & + a^2 \Delta \left\{ \int_0^t M[t - t'] A(x, t') \times \exp \left[- \int_{t'}^t kA(x, t'') dt'' \right] dt' \right\}. \end{aligned} \quad (19)$$

The velocity of the front was then obtained by means of the Hamilton-Jacobi approach via a hyperbolic scaling (a more elegant method known to lead to the same results as leading edge linearization in the Markovian case) and reads in our notation

$$v_{min} = \frac{k(\alpha - 3)}{\alpha - 2} \sqrt{\frac{a^2}{\tau} \left[\frac{k(\alpha - 3)}{\alpha - 2} \tau \right]^{1-\alpha} \frac{2 - \alpha}{k}} = \sqrt{k^{2-\alpha} K_\alpha \left(\frac{\alpha - 3}{\alpha - 2} \right)^{3-\alpha} (2 - \alpha)}, \quad (20)$$

with a generalized diffusion constant $K_\alpha = a^2/\tau^\alpha$.

Since the term quadratic in A does not contribute to the linearized solution determining the pulled front properties, the only difference between our approach and the one of the authors of Ref.[7] is that Eq.(19) is written for the concentration of the A-particles which are *created* during the reaction, while our equation Eq.(13) is put down for the B-particles which *irreversibly disappear*. Taking Eq.(19) for granted, we first checked that the method of the leading edge linearization used in the previous sections yields the same result for the minimal front velocity as in Ref.[7]. Therefore the differences between the results are not connected to the method applied, but to the equation itself.

The difference in the results is explained by the fact that the equations for particles which are created during the reaction under the conditions discussed look differently from Eq.(19): Since the particle making its step as A might have entered the corresponding site both as A and as B (and having undergone a transformation), the equation for the product of the reaction (in our case A) has to contain the Laplacians of both A and B -concentrations, as discussed in [13]. Moreover, considering reversible reactions put additional problems due to possible multiple $A \rightleftharpoons B$ transformations during the waiting time at one site [14]. Although

leading to the classical FKPP-results in the Markovian case, the equations proposed in [15] are not well suited for the description of particles created during the reaction and for reversible reactions under conditions discussed in the beginning of the paper.

IV. CONCLUSION

Let us summarize our findings. We considered the reaction-subdiffusion problem for the irreversible autocatalytic conversion reaction $A + B \rightarrow 2A$ which, in the case of normal diffusion, is described by the FKPP equation. We show that in the case of subdiffusion, under the assumption of the reaction taking place irrespectively on the particles' mesoscopic motion, the minimal front's propagation velocity is zero, suggesting the propagation failure. This regime can be considered as a result of a continuous transition to $D \rightarrow 0$ in the normal FKPP situation. The result obtained is in contrast to the treatment in [7] where the finite propagation velocity of a traveling wave was found. The differences in the assumptions of the two approaches (corresponding essentially to two *very different situations*) are discussed.

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